The hydrogeologic/hydrologic study report for CLL was prepared to demonstrate that the landfill will not cause or contribute to a violation of an Aquifer Water Quality Standard at the designated point of compliance. It also contains information which supports both the strategy for the suspension of groundwater monitoring, and the design components for the lateral expansion.

9.1 REGIONAL PHYSIOGRAPHY

The landfill site is situated in a geographic feature known as Cinder Lake. Cinder Lake is a relatively small dry sedimentary basin covering a regional area of approximately 5 square miles. It is located in the Colorado Plateau Physiographic Province and in the eastern part of the San Francisco volcanic field as described by Thornbury (1965). Topographically, the regional slope of the basin is from roughly north to south. The terrain is rugged and irregular and includes groups of dissected extinct volcanoes consisting of numerous cinder cones and associated flows and cinder deposits. Deposition of alluvial material in the basins between many of the extinct volcanoes has formed relatively flat and treeless areas referred to as "parks" (Cosner, 1962). Cinder Lake is one of these parks. Land surface elevations range from approximately 6,600 feet above mean sea level (amsl) to 6,700 amsl on the landfill property.

9.2 REGIONAL GEOLOGY

CLL is located in the Colorado Plateau Physiographic Province of northern Arizona. This part of the province is characterized by exposures of a relatively undisturbed sedimentary section consisting of Paleozoic through Mesozoic rocks (Thornbury, 1965). Disturbances to the sedimentary section include normal faulting, folding, and intrusions of igneous rocks.

Structural control of volcanic vents in the San Francisco volcanic field is suggested by the alignment of cinder cones along a linear trend, elongated cinder cones, dike-fed fissure ridges, and alignment of other volcanic features on known fault zones. Although surface structures may be masked by volcanic flows and cinders, the alignment of cinder cones within the study area may suggest that underlying structures are responsible for the alignment. No faults have been mapped in the immediate vicinity of the landfill; however, volcanic cover could mask the surface expression of any faults (WTI, 1991).

The area stratigraphy has been determined based on several data sources. These data sources include available driller's logs for wells drilled in the study area and published geologic and hydrogeologic studies (Arizona Department of Water Resources [ADWR], 1993a, McGavock, et. al, 1986; and Kluth and Kluth, 1974; and Cosner, 1962).

Cenozoic volcanic deposits and alluvium immediately underlie the surficial soils throughout the study area (Figure 9-1). These volcanics consist of basaltic lava flows and cinder cones. Cinders erupted from Sunset Crater, located approximately 4 miles north of the landfill, blanketing the low lying areas in the immediate vicinity and forming Cinder Lake. In some areas in the study area, the basaltic lava flows outcrop at the surface.

A sedimentary sequence underlies the Cenozoic volcanic deposits and comprises the following stratigraphic units, in order of increasing depth and geologic age: Moenkopi formation, Kaibab limestone, Toroweap formation, Coconino sandstone, Supai formation, Redwall limestone, and Martin formation (Table 9-1). The units in this sedimentary sequence do not outcrop within the area. The closest outcrop of this sequence is located along the eastern flank of Elden Mountain (Kluth and Kluth, 1974). Elden Mountain is located approximately 5 miles southwest of the

Site-Specific Geology 9.2.1

The site-specific geology data collected at the landfill property include data collected by WTI during its soil investigation in 1991 and by Woodward-Clyde during its geotechnical investigation in 1996. The maximum depth of the WTI investigation was about 55 feet below land surface (bls); the maximum depth of the Woodward-Clyde investigation was about 78 feet bls. Data collected during the these investigations have been used, in conjunction with available reports from government agencies and private entities, to extrapolate geologic conditions beneath the landfill property.

The geologic column underlying the landfill property is presented on Figure 9-2. The depth intervals for the various geologic units have been inferred based on available geologic logs and based on land surface elevations within the area (Table 9-2).

A volcanic sequence underlies the property to a depth of approximately 325 feet bls. This sequence is comprised of units identified as "cinder unit" and "basalt unit". The cinder unit, comprised of cinders interbedded with sandy clay/silty sand, is present in most areas of the property from land surface to approximately 10 to 60 feet bls. The clayey interbeds within the cinder unit have the potential to contain perched groundwater. WTI reported that no groundwater was encountered in the cinder unit during drilling performed as part of its 1991 soil investigation. Woodward-Clyde reported in their 1996 investigation that several borings encountered minor zones of moist to wet conditions typically within clayey interbeds.

In isolated areas of the property, a basalt unit crops out and forms small hills. However, in most areas of the property, the basalt unit underlies the cinder unit. This basalt unit is projected to exist at depths of approximately 10 to 60 feet bls to approximately 325 feet bls, based on driller's' logs. The basalt unit is highly interbedded, fractured, and laterally heterogeneous. The unit is reported to contain cinders at some locations. The basalt unit has been reported to contain perched groundwater in some areas.

A sedimentary section exists below the landfill property from the bottom of the basalt unit to depths of at least 1,800 feet bls. A relatively thin section of the Moenkopi formation is present immediately below the basalt unit. The Moenkopi formation exists at depths from approximately 325 feet bls to approximately 350 feet bls. The Moenkopi formation is comprised of siltstone and sandstone and may contain perched water where the formation is not highly fractured. Underlying the Moenkopi formation, the Kaibab limestone is present from approximately 350 feet bls to approximately 635 feet bls. The Kaibab limestone is comprised of jointed and thickbedded limestone and sandy limestone. The Kaibab limestone has not been documented to contain perched groundwater in the study area. Underlying the Kaibab limestone, the Coconino sandstone is present from approximately 635 feet bls to approximately 1,430 feet bls. The Coconino sandstone is comprised of firmly cemented sandstones with the lower portion comprising part of the regional aquifer where saturated. Below the Coconino sandstone, the Supai formation is present at depths of approximately 1,430 feet bls to greater than 1,800 feet bls. The upper portion of the Supai formation is comprised of sandstone and the lower portion is comprised of sandy siltstone. The upper portion of the Supai formation is part of the regional aquifer system in the vicinity of the landfill property.

SOILS 9.3

Regional Soils Data 9.3.1

Regional soil survey data indicate that surface soils in the vicinity of CLL consist of coarse sands, loamy sands, sandy loams, and loams derived from Quaternary-aged cinders. Area soils belong to the Typic Ustorthents, Vitrandic Argiborolls, Vitrandic Hapleborolls, and Vitrandic Ustochrept subgroups (Coconino National Forest, 1994). These soils have gravelly surfaces and subsoils and are of varying thickness over volcanic flows. The permeability of the regional surface soils is reported to be moderate to high. Area soils have been classified as "excessively drained," meaning the soils are very porous and rapidly permeable. Rainfall or snowmelt water would likely drain quickly through area surface soils (Soil Conservation Service, 1967; Coconino National Forest, 1994).

9.3.2 Site-Specific Soils Information

9.3.2.1 Soil Texture

WTI drilled 20 soil borings on the landfill property at locations within and on the perimeter of the landfilled area (Drawing 2). The borings were drilled with a hollow-stem continuous-flight auger to totals depths ranging from 13.5 feet bls to 55 feet bls. The borings were lithologically logged and drive samples were collected at selected intervals for chemical analyses. The WTI borings were drilled until auger refusal occurred. WTI interpreted auger refusal to coincide with the contact between the subsurface soil deposits and the underlying basalt unit (WTI, 1991).

Woodward-Clyde drilled 28 borings at locations within the existing landfill, the proposed lateral expansion area, and along the landfill perimeter (Drawing 2). These borings were advanced with a hollow-stem continuous flight auger to depths ranging from 6 to 79 feet. After refusal on bedrock, six of the borings were advanced with diamond-bit coring methods into the basalt layer. Woodward-Clyde also performed seismic refraction measurements along six profiles to evaluate the depth of the cinder/basalt contact.

Boring logs and sampling data collected by WTI and Woodward-Clyde are included as Appendix I. Review of the logs for the soil borings drilled at the perimeter of the landfill and within the lateral expansion area indicates an areal and vertical heterogeneous distribution of subsurface soils. Subsurface soils generally consist of interbedded layers of poorly graded sand with coarse grained volcanic cinders, sandy clays, clayey sands, and clayey gravel. Based on the borings and seismic refraction surveys, the top of the basalt unit is located at approximately 10 to 60 feet bls in areas on the perimeter of the landfill and between 45 to 70 feet in the lateral expansion area (WTI, 1991, Woodward-Clyde, 1997).

Review of the logs for the 12 soil borings (seven by WTI, five by Woodward-Clyde) drilled inside the landfilled area indicates that the vertical profile encountered consists of landfill soil cover, refuse, and approximately 5 to 20 feet of natural subsurface soils. Solid waste was encountered to depths ranging from 13 to 38 feet bls in this area. WTI interpreted the top of the basalt layer to exist at approximately 32 to 50 feet bls in the borings drilled within the landfilled area (WTI, 1991).

9.3.2.2 Soil Physical Characteristics

WTI collected samples of existing landfill cover materials and of subsurface soils within active portions of landfill excavations. The precise locations at which these samples were collected were not provided by WTI. The samples were analyzed for selected engineering properties. WTI's soils laboratory performed the following analyses of the samples: sieve analysis, Atterberg limits, remolded permeability, and moisture/density relationships. Results of the soil physical analyses have been summarized (Table 9-3).

9.3.2.3 Soil Chemical Quality

WTI submitted soil samples for chemical analysis from selected soil borings during their 1991 field investigation. Soil samples were collected from seven borings located inside the landfill (Drawing 2, boring numbers MW-2, MW-6, MW-11, MW-12, MW-13, MW-14, and MW-17). The samples were collected at depths ranging from 1.5 feet to 10 feet below the refuse mass. Soil samples were also collected from five WTI borings located on the perimeter of the landfilled area (borings numbers MW-1, MW-10, MW-15, MW-18, and MW-20). There was no boring number 9.

All samples collected by WTI were submitted to Westech Laboratories for chemical analysis and the results are presented in Appendix J. The laboratory analyzed the samples for the following inorganic constituents: arsenic, barium, cadmium, total chromium, lead, mercury, selenium, silver, ammonia-nitrogen, chloride, sulfate, total organic carbon, total organic halogens, and pH-solids. The results of the laboratory analyses have been summarized in Table 9-4a.

Ammonia-nitrogen, total organic carbon, total organic halogens, barium, cadmium, and total chromium were detected in one or more soil samples. Of the constituents detected, barium, cadmium, and total chromium currently have ADEQ Soil Remediation Levels (SRLs) for soil ingestion. All barium, cadmium, and total chromium concentrations detected in soil samples collected beneath the refuse and from soil samples collected from borings on the perimeter of the landfill were less than the respective SRLs for these constituents.

A simple statistical analysis was performed by WTI to compare the chemical quality of soil samples collected by WTI from the two groups of borings: perimeter borings and borings inside the landfill. The purpose of the analysis was to determine if there is any indication that chemical quality of soils collected from below the refuse has been significantly affected by fluids migrating from the refuse. Due to the limited number of soil samples collected, the focused analyte list for chemical analysis, and the wide variety of soil types sampled, the results of the analysis provides a qualitative indication of whether or not soils beneath the refuse have been affected. The analysis was performed by computing the mean and standard deviation of concentrations of individual constituents within each boring group. The results of the analysis suggest that concentrations of inorganic constituents detected in soils beneath the refuse are very similar to the concentration of these constituents detected in soil samples collected on the perimeter of the landfill.

Soil samples were collected by Woodward-Clyde for chemical analyses during the installation of five vadose zone monitoring stations in 1995. Boring logs and sampling data are included in Appendix I. Samples were submitted to Analytical Technologies, Inc. for chemical analysis and the results are presented in Appendix J. A summary of the results is presented in Table 9-4b and 9-4c. The samples were tested for volatile organic compounds, semi-volatile organics, chloride, sulfate, pH, total organic carbon and heavy metals.

Analytical results from Boring V-1 are used for comparison purposes because V-1 is located outside the landfill footprint and should represent naturally-occurring or "background" conditions in the soil/cinders layer underlying the site. The results indicate that the native soil and cinders material at the location and depths sampled in borings V-1 through V-5 do not appear to have been impacted by any of the constituents analyzed.

9.4 **HYDROGEOLOGY**

9.4.1 Regional Hydrogeology

The regional aquifer in the study area comprises the Supai and Coconino aquifer. The regional aquifer is recharged primarily from precipitation or snow-melt water percolating downward through the permeable rocks into the Coconino sandstone and the upper sandy portion of the Supai formation. Recharge to the regional aquifer occurs primarily in the area of the Mogollon Rim, located to the southwest of the study area. Recharge to the regional aquifer also occurs in the vicinity of Elden Mountain, where the Supai formation and Coconino sandstone are exposed at or near the surface.

Groundwater movement in the regional aquifer is toward the northeast (Figure 9-3). The elevation of the regional aquifer piezometric surface within the study area ranges from approximately 4,400 to 5,200 feet amsl based on studies performed by the U.S. Geological Survey (USGS) (McGavock et al., 1986).

Well yields in the regional aquifer range from less than 1 gallon per minute (gpm) to over 1,000 gpm. The yield of a properly constructed well depends on the saturated thickness penetrated by the well and the hydraulic conductivity of the aquifer at the well site. Depth to water in the regional aquifer is generally deep in study area wells, ranging from approximately 1,400 to 1,600 feet bls. Groundwater levels in the regional aquifer are generally too deep to economically install and operate a well for most domestic purposes (McGavock, et al., 1986).

Perched groundwater zones may occur in geologic units overlying the regional aquifer. Such conditions are generally limited to areas where quantities of recharge are high, but is impeded from movement to the regional water table by shallower units of relatively low hydraulic conductivity. The Cenozoic volcanic and Moenkopi formation are known to contain units that form perched groundwater zones in the Flagstaff area (Cosner, 1962). Examples have been noted in the vicinity of Rio de Flag.

9.4.2 Site-Specific Hydrogeologic Conditions

The site-specific hydrogeologic data collected at the landfill property includes data collected by WTI during its soil investigation in 1991, data collected by WCC during its soil investigation in 1996, and recent lysimeter sampling results. This data has been used, in conjunction with available reports from government agencies and private entities, to extrapolate hydrogeologic conditions beneath the landfill property.

9.4.2.1 Groundwater Occurrence and Movement

The only significant groundwater unit known to underlie the landfill is the regional Supai/Coconino aquifer. Depth to water in the regional aquifer is estimated to be approximately 1,600 feet below the landfill property, based on an average land surface elevation of 6,630 feet amsl and on a projected elevation of the regional aquifer piezometric surface of 5,030 feet amsl (Figure 9-3). As previously discussed, field data suggests that perched groundwater conditions may exist in clayey interbeds within the cinder unit beneath the landfill property. Insufficient information is available at this time to determine if perched groundwater units in the other geologic units overlying the regional aquifer.

Groundwater flow in the regional aquifer beneath the property is toward the northeast. Groundwater in the regional aguifer beneath the landfill flows toward T.23 N., R.9 E. Based on review of ADEQ records, no wells were identified within this township and range.

9.4.2.2 Groundwater Chemical Quality — Wells

Inorganic and organic water quality data are available for selected wells in the vicinity of the study area.

Inorganic Constituents

Inorganic water quality data were obtained from USGS database and ADEQ files for the Marijka, Koch Field, and Sunset Crater wells operated by the Doney Park Water Company (DPW) and one private well located at A(22-08)16dad (Table 9-5). All of these wells are completed in the regional aquifer.

Review of available data for inorganic constituents indicates that barium concentrations in wells tapping the regional aquifer may exceed the ADEQ AWQS for aquifers classified drinking water protected use. Additionally, it appears that barium concentrations in the some areas in the regional aquifer may also exceed both the EPA MCL for drinking water and the ADEQ HBGL for drinking water.

An unpublished study prepared for DPW suggests that elevated barium concentrations in the regional aquifer within the study area are naturally occurring and may be associated with recent volcanic activity (DPW, 1991).

No other inorganic constituents were reported at concentrations exceeding current AWQSs, MCLs, or HBGLs (Table 9-5).

Organic Compounds

Results of chemical analyses for organic compounds were collected from ADEQ files for DPW's Marijka, Koch Field, and Sunset Crater wells (ADEQ, 1993). Samples were collected from the three wells on July 1, 1992 and analyzed by Westech Laboratory, Inc. No organic compounds were detected in these samples (Appendix J).

9.4.2.3 Groundwater Chemical Quality — Lysimeter Results

A vadose zone monitoring system was installed in the fall of 1995 by Layne Environmental Services, Inc. (WCC, February 1996). The locations of the monitoring stations are shown in Drawing 2. At each monitoring station, lysimeters were installed in boreholes at the sediment/bedrock interface to monitor soil pore-water quality. Lysimeters were sampled in accordance with the "Standard Operating Procedures, Vadose Zone Monitoring Program" contained in Appendix K. Laboratory data has been subjected to a QA/QC review and has been found to be of satisfactory quality.

Vadose zone porewater samples were obtained during four sampling events which occurred on April 18 to 20, 1996, August 21 to 23, 1996, and May 5 to 8, 1997, and September 15 to 18, 1997 (City of Flagstaff, 1997). Results of these events are presented in Appendix J. Concentrations of chloride and sulfate were found to be higher in samples taken within the landfill than at the background station. Several metals, including arsenic, barium, iron, potassium, manganese, magnesium, nickel, and vanadium were also found to be higher in the monitoring stations within the landfill than at the background station. All chemical constituents detected above laboratory detectable limits were well below alert levels discussed in Section 10.1.1.

9.4.2.4 Groundwater Users

Groundwater users in the vicinity of the landfill include private users and DPW.

Groundwater users in the area were identified based on a records search conducted by Hargis + Associates, Inc. (H+A) in September 1993. The major groundwater users identified based on the well records search were DPW and private well owners. The following data sources were searched to identify wells of record within the study area:

- ADWR well registry (55-files) and driller's log files (ADWR, 1993a)
- ADWR registry of wells drilled prior to 1980 (35-files) and driller's log files (ADWR, 1993b)
- ADWR Groundwater Site Inventory database (ADWR, 1993c)
- Doney Park Water Company internal file data (Arizona Engineering Company, 1993) and
- Arizona Corporation Commission (ACC) annual utility report files (ACC, 1993).

Information regarding well location, well construction, and well ownership has been compiled for study area wells (Table 9-6). Locations of the wells identified are shown on the study area map (Figure 9-4). Subsurface lithology data were available for only seven wells located within the study area (Table 9-2).

Doney Park Water Company (DPW)

DPW provides water service to residential developments in the Doney Park and Black Bill Park areas. As of 1998, DPW served approximately 2,451 residential and 47 commercial accounts. DPW currently supplies its customers with groundwater pumped from seven wells. Three of DPW wells, identified as Koch Field, Marijka, and Sunset Crater wells, are located within the study area (Table 9-6). The remaining four wells are located south of the study area in T.21 N., R.9 E. Total depths of the DPW supply wells range from approximately 1,802 feet bls. Reported pumping rates from DPW supply wells range from approximately 18 gpm to approximately 230 gpm. A total of approximately 135 million gallons of water was served to DPW customers in 1991 (ACC, 1993).

Private Wells

A total of approximately 25 private wells have been identified in the area based on the results of the well inventory. The majority of the wells identified are located in T.22 N. R.8 E. (Table 9-6; Figure 9-5).

Wells in the immediate vicinity of the landfill property are shown on Figure 9-5. Three wells are located within a 2-mile radius of the landfill. None of the wells identified in the well inventory are located in areas downgradient of the landfill, based on groundwater flow direction in the regional aquifer system.

9.5 SURFACE WATER HYDROLOGY

The land surface within Cinder Lake slopes gently toward the south. Cinder Lake is covered by black volcanic cinders with higher topography surrounding the area. Cenozoic lava flows and cinder cones form the northern, eastern, and southern boundaries of Cinder Lake. The western boundary is comprised of Quaternary alluvium and colluvium and forms a gentle incline rising toward the San Francisco Mountains to the west (WTI, 1991).

Regionally, the area is drained by the Little Colorado River and its tributaries. Cinder Lake is located within the drainage basin of Rio de Flag. All of the tributaries to the Rio de Flag in the study area are ephemeral washes. No ephemeral washes are evident in the Cinder Lake area due to a combination of relatively flat topography and very high drainage capacity of the cindery soils. Several small basins of closed drainage have developed near Sunset Crater due to damming of washes by volcanic rocks. These basins include portions of Bonito, Black Bill, and Doney Parks (Cosner, 1962).

No significant surface water features exist within or near the landfill property and no 100-year floodplains exist on the property. The closest major stream within the study area is Rio de Flag,

located approximately 3.5 miles south of the landfill property. Rio de Flag is an ephemeral stream along its reach within the study area. Rio de Flag and its tributaries flow only in direct response to precipitation or snowmelt (Hill, Hales and Aldridge, 1988).

USGS measured and estimated peak flow rates for the water years 1970 through 1982 for the Rio de Flag at a location near Interstate Highway 40 (Section 7, T.21 N. and R.7 E.). The purpose of these estimates was to study storm runoff in the Flagstaff area. During the period 1970 through 1982, no flow occurred at this location during the water years 1974 and 1981. During the rest of the period, the maximum annual peak discharge estimated at the site was 421 cubic feet per second on December 19, 1978 (Hill, Hales and Aldridge, 1988).

9.6 DISCHARGE IMPACT ASSESSMENT

The results of vadose zone monitoring conducted since 1995 (see Section 10.1) appear to indicate that leachate migration from the landfill is not occurring. Additionally, neither WTI nor Woodward-Clyde observed leachate fluids during drilling through the landfill.

9.6.1 **Potential Fluid Migration Analysis— HELP Model**

The amount of percolation through a landfill is a function of precipitation, evaporation, evapotranspiration, type of cover material, type of vegetative cover, and the surface slope and condition. The Hydrologic Evaluation of Landfill Performance (HELP) computer model (version 3.05a) was used to analyze the potential for fluid migration through the landfill. The HELP model was designed to simulate water movement across, into, through, and out of landfills (Schroeder et al., 1992). This model accepts climatologic data as well as soil property data, and utilizes a solution technique based on the water budget concept, calculating runoff, infiltration, percolation, evapotranspiration, soil moisture storage, and lateral drainage.

Two general types of data are required for the model:

- climatologic data, which includes daily precipitation values, mean monthly temperatures, mean monthly solar radiation values, and growing season for vegetation, and
- soil property data, which includes soil porosity, field capacity, hydraulic conductivity, evaporative depth, the depth and type of different layers of soil in the landfill, placement quality and defect density for flexible membrane liners, and the Soil Conservation Service (SCS) Runoff Curve Number.

The model requires the user to specify the vertical profile of the landfill by identifying the purpose of design for each layer. Layers can be designed to provide vertical percolation, lateral drainage, or to act as a hydraulic barrier. Input parameters also include the fraction of the area where runoff is possible. Daily rainfall data may be input by the user, generated stochastically by the model, or taken from the model's historical database. The model's historical database contains five years of daily precipitation for 102 U.S. cities, for the period of 1974 through 1978. Daily temperature may be input by the user or generated stochastically. Solar radiation data are generated stochastically.

The HELP model calculates the amount of runoff based on the SCS Curve Number method. This method takes into account factors such as soil type, land use, and vegetative cover to choose a curve number. In this method, soils are classified into four hydrologic soils groups. Each of these hydrologic soil groups refers to a specific soil's ability to absorb water, which is a measure of the soil's permeability. The higher the curve number, the lower the permeability, and the higher the volume of runoff. An SCS Curve Number of 59 was selected assuming surface soils have low runoff potential (high infiltration rates) and that ground vegetation is non-existent to minimal (Ponce, 1989).

The rate of evaporation from a landfill cover is a function of solar radiation, temperature, humidity, vegetation type and growth stage, surface wetness, soil water content, and other soil characteristics. The HELP program uses a modified Penman method to compute potential evapotranspiration. Evapotranspiration is estimated based on the following three components:

- evaporation of water retained on foliage or on the landfill surface,
- evaporation from the soil, and
- transpiration by plants.

In calculating the amount of transpiration from plants, factors such as the maximum leaf area index and growing season are considered. The maximum leaf area index is the ratio of total leaf surface to soil area, which varies during the plant life. Daily percolation into the landfill is determined indirectly from a surface water balance calculation. Each day, infiltration is assumed to equal the rainfall minus the sum of runoff and evapotranspiration. The user-specified evaporative depth is the maximum depth from which moisture can be removed by evapotranspiration. A storage-routing procedure is then used to redistribute the soil water among the modeling segments that comprise the subprofile.

Leakage through geomembranes that may result from manufacturing and installation defects and by vapor diffusion is estimated by equations compiled by Giroud et al. (1989, 1992).

9.6.1.1 Site-Specific Precipitation Data

Daily rainfall and temperature data was obtained from Sunset Crater Monument (Flagstaff, Arizona). Daily precipitation and temperature data are available from 1969 to 1995. The average annual precipitation for this period was 17.06 inches. For the purpose of this simulation, five consecutive years were selected (1990 through 1994). This period, with a total of 100.61 inches of rainfall, and 20.12 inches of average annual precipitation comprised the wettest five consecutive years in the last 26 years of record. Average monthly rainfall and temperature data for this five-year period were entered into the HELP model. Based on these averages, the model stochastically generated daily precipitation and temperature data to evaluate the average annual percolation into the landfill.

The HELP model was run for the three areas at the landfill site:

- The existing unlined portion of the landfill;
- A 1-acre area outside the landfill; and
- The lined lateral expansion areas that are planned for future construction.

Both operational and post-closure conditions were modeled for the existing and lateral expansion areas. The following sections describe the program input and results.

9.6.1.2 Existing Unlined Landfill — Operational Condition

The existing unlined landfill was modeled using a two-layer configuration. Layer 1, a two-foot intermediate cover, was assigned a soil texture number of 12 based on the limited data collected by WTI and Woodward-Clyde on cover soils used at the landfill. The HELP User's Guide specifies default soil data for soil textures 1 through 18 (Schroeder et al., 1994). For a soil texture number of 12, input values for wilting point, field capacity, and porosity were 0.210, 0.342, and 0.471, respectively. A saturated hydraulic conductivity of 4.2 x 10⁻⁵ cm/sec was used which corresponded to a soil texture number of 4.

Layer 2 consisted of 28 feet of refuse material. The 28-foot layer is based on a visual estimate from an "equal refuse" thickness based on information from the on-site borings conducted by WTI. A soil texture number of 18 was used based on the HELP User's Guide specification for refuse material. Based on a soil texture number of 18, input values for wilting point, field capacity, and porosity were 0.077, 0.292, and 0.671, respectively. A saturated hydraulic conductivity of 1.0×10^{-3} cm/sec was used which corresponded to a soil texture number of 18.

An area of 108 acres was used for the existing landfill footprint. This scenario assumes that runoff is only possible on 80% of the modeled area.

9.6.1.3 Existing Unlined Landfill — Post Closure Condition

The existing landfill was modeled with post closure conditions by including a cover system composed of an 18-inch fill layer, a 6-inch lateral drainage layer, a 60-mil HDPE flexible membrane liner, underlain by 12 inches of intermediate cover materials. The refuse column was assumed to be 100 feet thick. The fill materials were assigned a soil texture number of 3, with input values for wilting point, field capacity, and porosity of 0.047, 0.105, and 0.437, respectively. A saturated hydraulic conductivity of 3.1 x 10⁻³ cm/s was used, corresponding to a soil texture number of 3. The lateral drainage layer was assigned a soil texture number of 2, with input values for wilting point, field capacity, and porosity of 0.024, 0.062, 0.437, respectively. A saturated hydraulic conductivity of 5.9 x 10⁻³ cm/s was used, corresponding to a soil texture number of 2. Placement quality of the flexible membrane liner was assumed to be 'poor'; frequency of manufacturing defects (pinholes) was assumed to be 1 per acre; and the frequency of installation defects was assumed to be 4 per acre. A saturated hydraulic conductivity of 2.0 x 10⁻¹³ cm/sec was used for the HDPE liner.

This scenario assumes that surface water runoff may occur on 100% of the modeled area.

9.6.1.4 One-Acre Area Outside the Landfill

The HELP model was also run for a one-acre area comprised of one 14-foot soil layer to provide a comparison to background conditions. The soil layer was assigned a soil texture number of 4. Although the surface cinders are thought to be rapidly draining, a hydraulic conductivity of 1.7 x

10⁻³ was selected since the natural soils contain alternating cinder and clayey cinder units. Based on a soil texture number of 3, input values for wilting point, field capacity, and porosity were 0.047, 0.105, and 0.437, respectively. This scenario assumes that no surface runoff occurs from the area.

9.6.1.5 Lined Lateral Expansion Areas — Operational Condition

The operational condition of the expansion area was modeled with two liner configurations: the prescribed Subtitle D liner, and an alternative liner discussed in Section 8. An area of 20 acres was used to model a typical expansion area cell. These scenarios assume that the runoff is only possible on 80% of the area.

The prescriptive Subtitle D liner was modeled with five layers: a 12-inch intermediate cover layer, a 12-foot column of refuse materials, a 2-foot lateral drainage layer, a 60-mil HDPE liner, and a 2-foot compacted clay layer. The parameters used to represent the intermediate cover, refuse, lateral drainage, and HDPE liners are identical to those used to model the existing landfill (see above). The compacted clay layer was assigned a soil texture number 16. Values for wilting point, field capacity, and porosity of the clay layer were 0.367, 0.418, and 0.427, respectively. The hydraulic conductivity of the clay soil was assumed to be 1.0×10^{-7} cm/s.

Six layers were considered in modeling of a GCL-lined lateral expansion cell: a 12-inch intermediate cover layer, a 12-foot column of refuse materials, a 1-foot buffer layer, a 1-foot lateral drainage layer, a 60-mil HDPE liner, and a 0.33-inch GCL. The parameters used to represent the intermediate cover, refuse, lateral drainage, and HDPE liner layers are identical to those used to model the existing landfill, (see above). The buffer layer was assumed to be similar to intermediate cover materials, and was assigned a soil texture number of 12. The 0.33-inch GCL barrier layer was assigned a soil texture number of 17. Values for wilting point, field capacity, and porosity of the GCL layer were 0.400, 0.747, and 0.750, respectively. A saturated hydraulic conductivity of 3.0x10⁻⁹ cm/s was used for the GCL layer.

9.6.1.6 Lined Lateral Expansion Areas — Post Closure Condition

The lined lateral expansion areas were modeled for a post closure condition assuming that the cover would be composed of 18 inches of fill, 6 inches of sandy lateral drainage materials, a 60-mil HDPE liner, underlain by a 0.33-inch GCL. The refuse column was assumed to be 120 feet thick and to be overlain by 12-inches of intermediate cover. The refuse was assumed to be underlain by the alternative base liner system described above. The parameters used to represent the intermediate cover, refuse, lateral drainage, and HDPE liners are identical to those used to model the existing landfill. The parameters used to model the GCL liner are identical to those used to model the lateral expansion area during operating conditions, (see above).

The post-closure condition of the expansion area was also modeled with a monolithic cap of compacted cinder/soil materials. The cap was assumed to be 3.5-feet thick and underlain by a 120 foot thick refuse column. The refuse was assumed to be underlain by the base liner system described above. The monolithic cap materials were assigned a soil texture number 6. Values for wilting point, field capacity, and porosity of the clay layer were 0.453, 0.190, and 0.085,

respectively. The hydraulic conductivity of the barrier soil was assumed to be 7.2x10⁻⁴ cm/s, which is slightly slower than the values previously used for cinder because the soil will be compacted.

9.6.1.7 HELP Model Results

A summary of HELP modeling results is presented in Table 9-7. HELP Output files are presented in Appendix L. The results of the HELP modeling indicate that for a 2-foot landfill cover with a hydraulic conductivity of 4.2×10^{-5} cm/sec, and a SCS runoff curve number of 59, with an underlying 28-foot refuse layer, approximately 1.84 inches of percolation is expected to occur through the refuse layer per year from the existing unlined landfill. Essentially no percolation $(8.5 \times 10^{-4} \text{ to } 7.0 \times 10^{-3} \text{ inches annually})$ is expected from the lined lateral expansion area during operational conditions.

The computed amount of percolation through a 14-foot soil layer outside the landfill with a hydraulic conductivity of 1.7×10^{-3} cm/sec, and a SCS runoff curve number of 59 is 5.35 inches per year.

Percolation rates for closure rates for both the existing and lateral expansion areas are expected to be less than 0.00001 inches annually. If a monolithic cap is constructed as the cover for the expansion areas, annual percolation rates are expected to be less than 7.0×10^{-3} inches.

The low rate of percolation estimated by the HELP modeling at the landfill is likely due to the following:

- The overall annual precipitation rate at Cinder Lake is reasonably low.
- The distribution of the rainfall is in a pattern that allows the soil moisture to evaporate more than percolate.

It should be noted that continued vadose zone monitoring (see Section 10.1.1) will provide additional data related to the actual migration of moisture from the landfill.

9.6.2 Potential Contaminants

CLL has operated over a 30-year period during which the bulk chemical quality of the refuse could have varied somewhat. As such, it is not possible to definitively characterize the list of potential contaminants that are actually present in the existing portion of the landfill. The potential contaminants in the refuse mass were therefore identified based on scientific literature for similar municipal solid waste landfills. A compiled list of potential contaminants was prepared including trace metals, common ion constituents, and organic compounds (Table 9-8). In addition, vadose zone monitoring results from 1996-1997 (Appendix J) were reviewed to help identify potential contaminants.

The HELP model evaluation suggests that leachate fluids could potentially migrate from the existing portion of the landfill during operation but essentially not from the lined lateral expansion area.

The possibility that potential contaminants could be transported from the refuse mass to groundwater depends on several factors:

- Whether the contaminant is present in leachate migrating from the base of the landfill at concentrations that could result in violation of a ADEQ AWQS or EPA MCL for drinking water.
- Whether fluids can migrate through the approximate 1,600 foot unsaturated zone and at high enough concentrations and in sufficient quantities to impact groundwater quality in the regional aquifer system.

9.6.3 Multimedia Exposure Assessment Model

The Multimedia Exposure Assessment Model (MULTIMED) computer model was used as an analytical tool to evaluate the likelihood that contaminated fluids migrating from the base of the landfill can reach the regional aquifer at high enough concentrations to significantly impact the chemical quality of the regional groundwater. The MULTIMED model simulates the movement of contaminants leaching from a waste disposal facility. The MULTIMED model is intended for general exposure and risk assessments of waste facilities and for analysis of the impacts of engineering and management controls (Salhotra et al., 1993 and EPA, 1992).

The MULTIMED model includes modules that simulate releases from a solid waste facility to air, soil, surface water, and groundwater. When applying MULTIMED to a solid waste facility regulated under Subtitle D, EPA requires that the user only utilize those modules associated with flow and transport through the unsaturated and saturated zones.

EPA has outlined a six step procedure for application of the MULTIMED model to evaluate the fate and transport of contaminants released from a solid waste disposal facility (Salhotra et. al, 1990). The EPA procedure is presented below in bold text followed by information regarding application of this procedure to modeling performed for CLL:

1. Collect site-specific hydrogeologic data.

Available site specific data were collected and are included in this document. These data are summarized in previous sections.

2. Based on water level measurements, determine whether or not the unsaturated zone modules should be active in the simulation.

Use of the unsaturated models is valid given the approximately 1,600 feet thickness of geologic materials lying between the base of the landfill and the regional aquifer system. Five layers were used to simulate the materials in the unsaturated zone. The five layers correspond to the following geologic units: cinder unit, basalt unit, Moenkopi formation, Kaibab limestone, and Coconino sandstone (Figure 9-2).

3. Determine contaminant to be simulated and determine the chemical properties of the selected contaminant.

A hypothetical contaminant that simulates the transport property of a conservative common ion, such as chloride, was selected for this simulation. The hypothetical common ion

contaminant is assumed to be non-biodegradable, non-sorbing to vadose zone materials, and assumed not to decay during transport. The hypothetical contaminant is also assumed to be non-sorbing to aquifer materials during groundwater transport. Therefore, the hypothetical common ion represents an extreme worst-case contaminant.

4. Determine landfill design and determine volumetric flow rate, or infiltration rate, from the bottom of the landfill into the unsaturated zone. Infiltration rate can be determined using a water balance model, such as the HELP model.

The current configurations of the existing unlined landfill and the lateral expansion areas were used in the simulation. The infiltration rate from the landfill was assumed to be equivalent to the average percolation rate from the base layer as calculated by the HELP model Section 9.6.1.

5. Select model input parameters and select a receptor location within the aquifer underlying the site. The receptor location must be selected directly downgradient of the landfill. Select an initial leachate concentration. Run MULTIMED using the steady state simulation.

Model input parameters were selected based on soils data, geologic data, and hydrogeologic data collected for the site. Input parameters were selected based on parameter estimation guidance contained in Salhotra et. al (1990). MULTIMED input parameters are listed in Table 9-9.

Two receptor locations were selected in the regional aquifer. The first receptor is located at the boundary of the landfill property, approximately 250 feet downgradient of the edge of the refuse mass. The second receptor is located 1 mile downgradient of the landfill property boundary.

The initial leachate concentration of the hypothetical contaminant was set to 1 milligram per liter (mg/l). This initial concentration is recommended in the MULTIMED guidance in order to simplify the computation of a dilution attenuation factor (DAF) for the contaminant. This recommendation is based on the fact that the MULTIMED estimate of concentration at a receptor location is linear with respect to initial leachate concentration. Therefore, the DAF is the factor by which the concentration is expected to decrease between the base of the landfill and the receptor location in the regional aquifer.

6. Using the concentration projected by MULTIMED at receptor location, compute a DAF by dividing the initial leachate concentration by the concentration at the evaluation point.

Since an initial leachate concentration of 1 mg/l was used for the MULTIMED simulation, the DAF is computed using the following equation:

$$DAF = \frac{1 \text{ mg/l}}{Concentration \text{ at Receptor Location, mg/l}}$$

9.6.3.1 Results and Discussion

The MULTIMED model was run to project the concentration of the hypothetical contaminant for the two receptor locations for the base cases using initial estimates of chemical, unsaturated zone, and aquifer parameters (Table 9-10). As mentioned previously, the model was run assuming that no mechanisms exist that could attenuate contaminant transport in the vadose zone. Therefore, the concentration of the contaminant reaching the base of the vadose zone is identical to the steady-state input concentration of 1 mg/l. Assuming no attenuation in transport is very conservative and would provide a simulation of the reasonable worst-case estimate of DAF at each receptor location.

9.6.3.2 Existing Landfill

Results of the base case MULTIMED simulations for the existing landfill indicated that the DAF for the hypothetical contaminant was 9 for the receptor at 250 feet from the edge of the refuse and 100 for the receptor 1 mile downgradient of the landfill boundary. concentrations at the two receptor locations were most sensitive to the estimates of aquifer parameters including saturated zone thickness, mixing zone depth, and hydraulic conductivity. MULTIMED was run for additional simulations varying the values of these three aquifer parameters (Table 9-10).

The results of the MULTIMED base case and sensitivity simulations suggest that:

- 1. DAFs ranged from approximately 1 to 20 for the hypothetical contaminant at the groundwater receptor located 250 feet from the edge of landfill. The average DAF was approximately 10. The computed solute concentration at this receptor point was most sensitive to changes in hydraulic conductivity estimates for the regional aquifer.
- 2. DAFs ranged from approximately 50 to 100 for the hypothetical contaminant at the groundwater receptor located one mile from downgradient from the landfill boundary. Although this range of DAF appears to be fairly broad, it is based on the difference in projected solute concentration of only ± 0.01 mg/l.

The results of the screening level MULTIMED simulation suggest that given the worst case assumptions regarding contaminant transport through the 1,600 feet of unsaturated zone, the average DAF for groundwater receptors located immediately next to the landfill could potentially exceed the optimum value of 100 as recommended in MULTIMED guidance (Salhotra et. al, However, using the same conservative assumptions, the DAF computed for a groundwater receptor located one mile from the landfill was close to 100 percent. The results of the well inventory performed for this study indicated that no groundwater users of record exist for a distance of at least 7 miles downgradient of the landfill (Figure 3-6).

To further evaluate potential leachate migration and the effect of the thick subsurface vadose zone underlying the site on leachate migration, the leachate travel times have been estimated. Travel time was estimated using Darcy's equation, which states that apparent velocity is directly proportional to the hydraulic conductivity and the gradient. Because the actual gradient between the landfill and the groundwater table is unknown, a conservative value of -1.0 was selected for the gradient. In addition, because of the difficulties associated with estimating unsaturated hydraulic conductivities, saturated hydraulic conductivities were used to represent the materials in the vadose zone. Only advection was considered. Based on these assumptions, the estimated travel time for leachate to reach the regional aquifer is over 900 years (Appendix L). Based on these extremely conservative assumptions, leachate would migrate downward approximately 101 meters downward in 52 years, the projected operational life of the unlined portion of the landfill (from 1965 when the landfill opened to 2017, the projected date that the unlined landfill will reach capacity and will be capped). It should be noted that the extremely conservative nature of this projection is confirmed by the results of chemical analysis of soil samples collected from beneath the landfill as well on-going vadose zone monitoring.

9.6.3.3 Lateral Expansion Areas

Results of the base case MULTIMED simulations for the lateral expansion areas indicated that the DAF for the hypothetical contaminant is at least 1 order of magnitude greater than 100, the recommended optimum value, for both receptor distances of 250 feet and 1-mile (Table 9-10). MULTIMED was run for additional simulations varying the saturated zone thickness, mixing zone depth, and hydraulic conductivity of the aguifer (Table 9-10).

These MULTIMED simulations strongly suggest that leachate infiltrating the lined expansion areas will not negatively impact the regional aquifer.

9.7 POINT OF COMPLIANCE

The selected point of compliance monitoring for the landfill is in the vadose zone in the cinder unit along a horizontal plane lying immediately below the base of the landfill. The rationale for selection of vadose zone as the point of compliance is the 1,600 foot thick column of heterogeneous geologic materials lying between the base of landfill and the regional aquifer Additionally, this site feature affords a significant opportunity for early warning detection considering the vertical distance to the regional aquifer.